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1st Virtual European Conference on Fracture

## On the elastic properties of PVC foam

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## Abstract

In the last decade, sandwich structures spread a great interest in civil engineering applications. However, despite their excellent mechanical performance, they can be affected by macroscopic and microscopic damages, which may trigger catastrophic failure modes. Detailed understanding of the physical and mechanical properties is needed in order to allow refined numerical models to describe structural behaviour under intensive loading conditions, accurately. The elastic and fracture characterisation of the core material is particularly relevant because cracking phenomenon strongly reduces the capacity of the sandwich structures to carry out loads. PVC foams, typically used as the inner core in a structural application, are investigated over a range of foam densities. PVC foams H100, H130, and H200, produced by DIAB. The elastic properties of foams under compressive uni-axial loading are measured using the full-field methodology.

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**Keywords:** Sandwich Structures; PVC foam; DIC.

## 1. Introduction

Due to their excellent mechanical and physical properties (low density, energy absorption, high insulation), cellular polymeric foams are extensively utilised in many industrial applications (Funari et al. (2019)). In particular, PVC foams are currently adopted for manufacturing different engineering structures and products such as cores of the sandwich panels. Skins can be made of metals or fibre-reinforced composites, materials that are showing an increasing success in civil engineering applications (Funari et al. (2016), Bruno et al. (2020), Funari et al. (2020), Stepinac et al. (2018) Funari et al. (2019), Fabbrocino et al. (2019), Funari et al. (2018), Spadea et al. (2017), Fabbrocino et al. (2020), Funari et al. (2017)).



In particular, the core has the task to transfer shear between the sheets when the panel is subject to bending loads. The intensive loading conditions to which sandwich structures are subjected might produce failure modes such as the skin/core debonding (Burlayenko et al. (2019), Burlayenko and Sadowski (2014), Funari et al. (2018), Funari et al. (2018)) and the crack kinking propagation in the core region (Martakos et al. (2019), Funari et al. (2019)). With reference to the crack kinking propagation in the core region, the assessment of the elastic and fracture properties of the PVC foams is an essential prerequisite to correctly implement a numerical model, which will be able to simulate deviation of crack trajectory from the initial direction (Funari and Lonetti (2017), Funari et al. (2016), Funari et al. (2019)).

As a matter of fact, macroscopic elastic characterisation of cellular foams is a challenging problem because of their hyperelastic behaviour and tendency for deformation localisation due to local collapse of cells under compression (Daniel and Cho (2011)). With the aim to detect the elastic properties of foam panels, many experimental procedures have been proposed in the last decade. Viana and Carlsson (2002) investigated the elastic properties of cross-linked PVC with nominal densities of 36, 80, 100, 200 kg m<sup>-3</sup>. In order to define the degree of anisotropy, they performed tension tests oriented in both in-plane and through-the-thickness of the foam panels, in which the strain field was detected by adopting an MTS extensometer. The behaviour of the PVC was found to be nearly isotropic. Wang et al. (2013) and Taher et al. (2012) developed a modified Arcan fixture to characterise all the elastic coefficients of an orthotropic polymeric foam material carrying out one single test where the Digital Image Correlation (DIC) and the Virtual Fields Method (VFM) were used. Zhang et al. (2012) defined an experimental setup to measure the material properties of polymeric foam at elevated temperatures. They focused on Divinycell PVC H100 foams carrying out tensile and compressive tests in a temperature-controlled chamber with temperatures ranging from 20°C to 90°C. In this case, the geometry of the samples was selected in accordance with the prescriptions defined in the ASTM Standard (2010). In order to remove the parasitic effects intrinsically presented in the experimental setup, a full-field methodology to detect the strain fields (DIC) was adopted. They obtained that the material is highly anisotropic with a ratio between the in-plane and through-thickness stiffnesses approximately equal to 0.5. Similar tests were conducted by Colloca et al. (2012), which investigated the behaviour of PVC foams with varying densities under both quasi-static and impact tests.

The present study aims at proposing an experimental method to measure the elastic properties of PVC foams featured by different densities, ranging from 100 to 200 kg m<sup>-3</sup>. The work is organised as follows. Section 2 describes the compression tests. Final remarks and conclusions are discussed in Section 3.

## 2. Compression Tests

According to ASTM Standard (2010) (Standard Test Method for Compressive Properties of Rigid Cellular Plastics), cubic samples with side length equal to 60 mm were tested to detect the elastic properties of the foams in compression. The samples were cut from 60 mm Divinycell panels in the two main directions using a Denford CNC router with a 0.1 mm resolution equipped with a 3 mm drill bit. Uniaxial tests were performed along the three main directions of the panel to investigate the expected transversally isotropy of the material, which is due to the manufacturing method.

The experimental setup consists of an Instron 4204 electromechanical universal testing machine equipped with a 50 kN load cell. As shown in Fig. 1, the load was applied by using a compression device embedding a spherical seating mechanism and two aluminium plates to apply the load uniformly on the specimen. Furthermore, in order to detect the specimen deformation by-passing the compliance of the load application system, a displacement transducer (DT) was used to measure the distance between the two plates. Furthermore, a Digital Image Correlation (DIC) system, consisting of a high-res digital camera employed in manual mode, and two high frequency led lights (Fig. 1) was also employed. The main purpose of using DIC was to analyse the strain distribution in the specimen. A picture every 0.5 sec. (2 Hz) was taken during the test with the purpose to monitor the front surface of the cube during testing phases, whereas LED lights were used to provide the necessary image contrast. A stream of black paint was preventively applied on the monitored specimen face as to obtain a random b/w speckle pattern, the ideal reference system for DIC purpose.



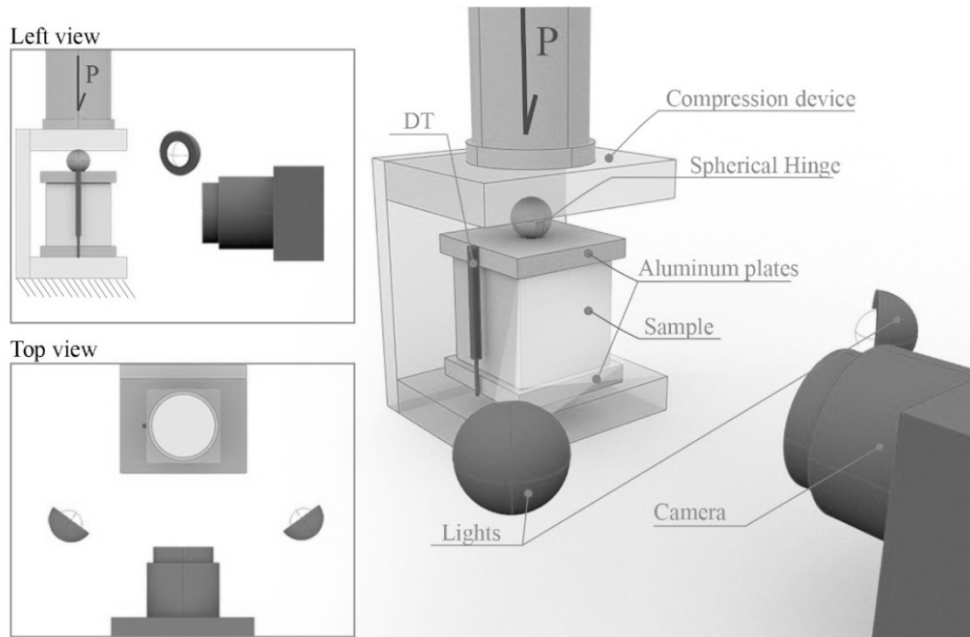


Fig. 1 Compressive Tests: experimental setup.

Fig. 2(a) and (b) show the envelope of stress-strain curves obtained by the five tested samples for all type of materials investigated (H100, H130, H200), for both through-the-thickness and in-plane directions. The engineering stresses reported on the vertical axis of the Figures are computed as the detected load, by the load cell of the machine, divided by the contact cross-section of the samples that are 60 mm × 60 mm. On the horizontal axis are reported the vertical strains that are obtained as the ratio between the detected shortening and the initial length of the sample, which is equal to 60 mm. On the basis of a preliminary analysis of the results reported in Fig. 2(a) and (b), it is clear that both, elastic moduli and compressive strengths exhibit increasing values with the increasing of the foam density.

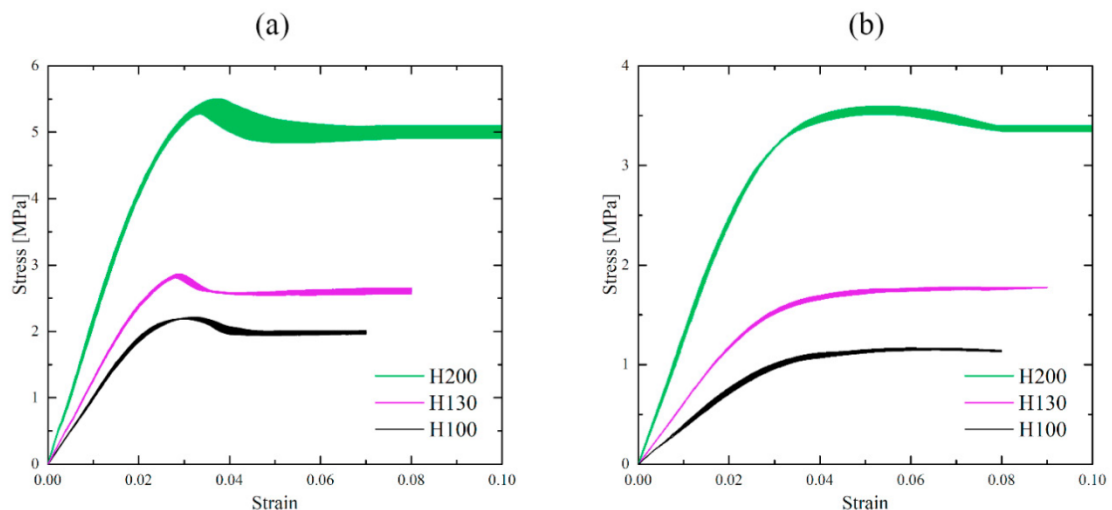


Fig. 2 (a) Compressive Tests: Uni-axial tests: through-the-thickness Stress-Strain curves.; (b) Compressive Tests: Uni-axial tests: in-plane Stress-Strain curves.



Table 1. Elastic properties Divinycell H 100, 130 and 200: through-the-thickness.

PVC Foam	DIAB		DT		DIC	
	$E_{th}$ [MPa]	$\nu_{xy}$	$E_{th}$ [MPa]	$\nu_{xy}$	$E_{th}$ [MPa]	$\nu_{xy}$
H100	135	-	102	-	141	0.42
H130	170	-	127	-	173	0.43
H200	310	-	223	-	312	0.43

Table 2. Elastic properties Divinycell H 100, 130 and 200: in-plane.

PVC Foam	DIAB		DT		DIC	
	$E_{ip}$ [MPa]	$\nu_{xz} = \nu_{yz}$	$E_{ip}$ [MPa]	$\nu_{xz} = \nu_{yz}$	$E_{ip}$ [MPa]	$\nu_{xz} = \nu_{yz}$
H100	-	-	39	-	56	0.38
H130	-	-	60	-	83	0.39
H200	-	-	130	-	154	0.41

As shown in Tab. 1, a remarkable difference between the average experimental elastic moduli detected by using DT system and the ones declared by the producer data sheet were obtained. This phenomenon is described in the scientific literature by researchers that have analysed the compressive behaviour of PVC foam. As a matter of fact, PVC foams show a hyperplastic behaviour and during compressive tests the deformations are concentrated in the mid region of the sample, producing the local collapse of the cells. This phenomenon may generate erroneous evaluations of the elastic properties of this materials

In order to overcome this problem, DIC was also employed to monitor the displacements field and consequently to compute strain on the monitored specimen face. The freeware Matlab script Ncorr, developed by Blaber et al. (2015) was employed to process the acquired images. This technique was employed to work out a good estimate of the local strain in the core of the specimen. Considering the total surface of the sample is 60×60mm, the measurement area has been set to 30×30mm in order to remove the edge effects. Average deformations, obtained through DIC in the measurement area, were linked to the loading values measured through the load cell, using the time as sorting variable. Three different loading stages were finally considered in the elastic range to estimate the elastic modulus of the material under uniaxial compression. Figs. 3-8 show the strain maps obtained by DIC for different load levels. As reported in Fig. 3, for the Divinycell H100 thorough-the-thickness, the strain maps are reported for three different load level equal to 0.25, 0.50 and 0.75MPa.

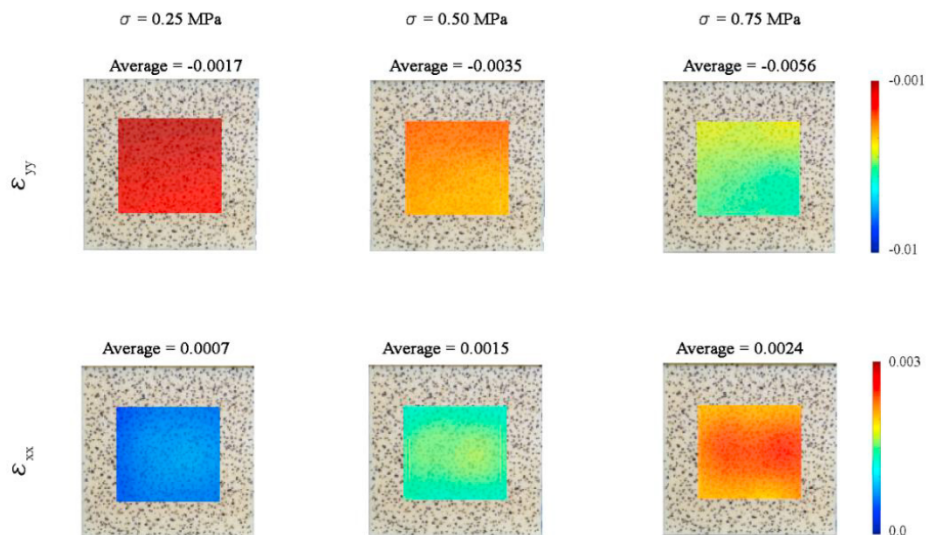


Fig. 3 Divinycell H100 thorough-the-thickness: strain maps obtained by DIC for different load levels (0.25, 0.50 and 0.75 MPa).

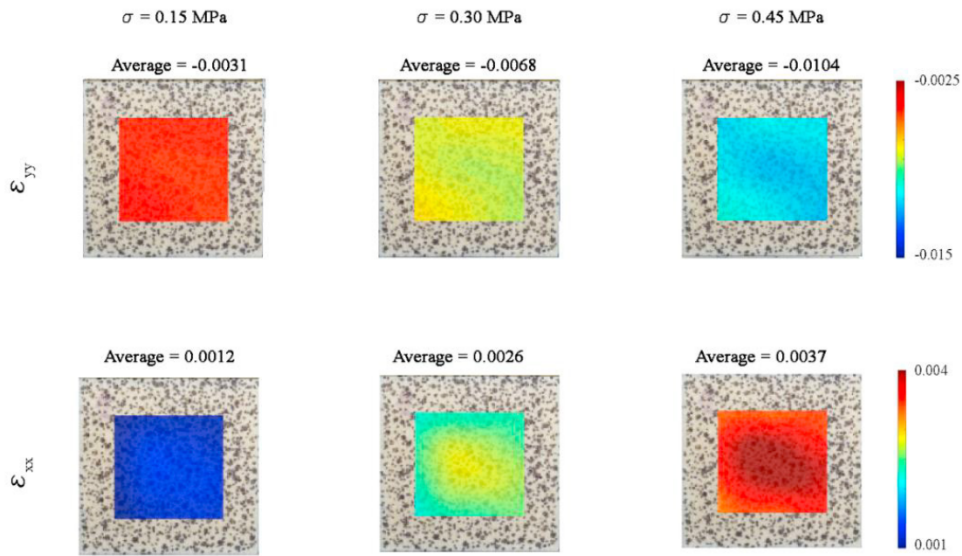


Fig. 4 Divinycell H100 in-plane: strain maps obtained by DIC for different load levels (0.15, 0.30 and 0.45 MPa).

On the basis of the average strain along the X and Y direction, an elastic modulus equal to 141 MPa was obtained, whereas the Poisson coefficient is obtained as the ratio between the horizontal and the vertical strain. In this case, the data are quite in agreement with those declared by the producer datasheet with a percentage error of almost 5%. Divinycell H100 in-plane direction was analysed for three load level in the elastic range equal to 0.15, 0.30 and 0.45 MPa, respectively. It is evident that the PVC foam H100 presents a reduced in-plane stiffness with a value of the elastic modulus and a Poisson coefficient equal to 56 MPa and 0.38, respectively. In this case, the experimental results are not comparable with those of the producer because they are not available. However, the results obtained in the present study are quite in agreement with those available by Wang et al. (2013).

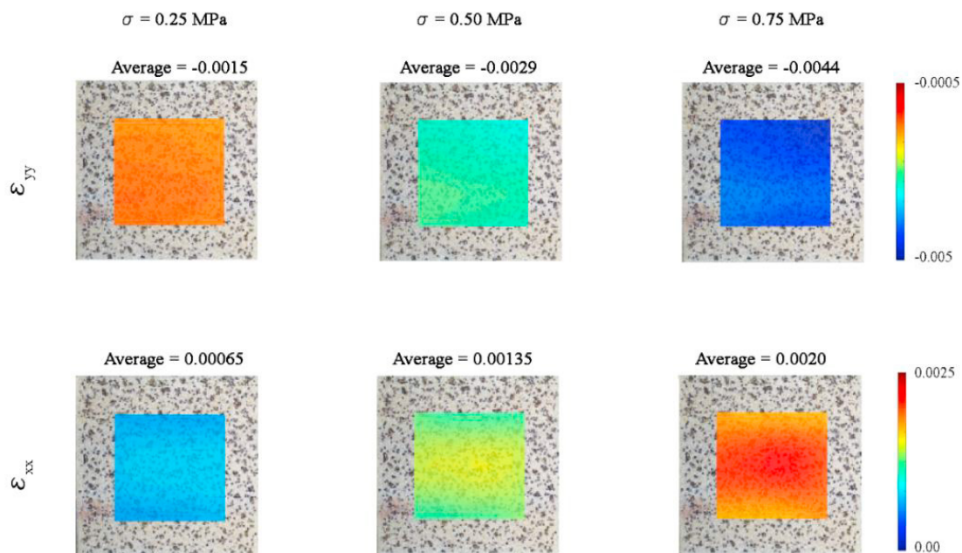


Fig. 5 Divinycell H130 through-the-thickness: Strain Maps obtained by DIC for different load levels (0.25, 0.50 and 0.75 MPa).



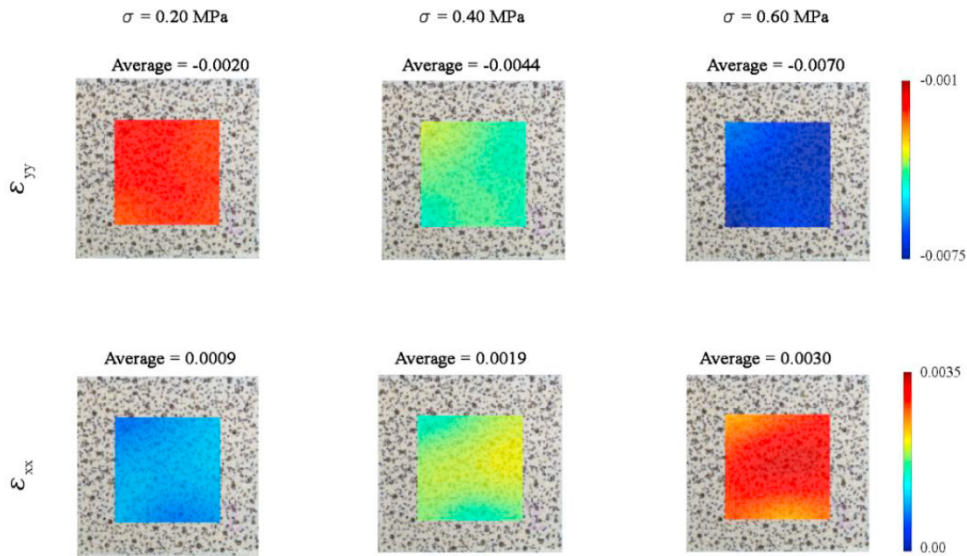


Fig. 6 Divinycell H130 in-plane: Strain Maps obtained by DIC for different load levels (0.20, 0.40 and 0.60 MPa).

In Fig. 5 the behaviour of the PVC H130 along the thorough-the-thickness direction were evaluated. In this case, the strain maps have been detected for the same load level adopted for the foam H100. The value of the elastic modulus obtained by using the DIC procedure is quite similar to those declared by DIAB company. A percentage error equal to 2% was obtained. As shown in Fig. 6, the PVC H130 foam, in the case of the in-plane direction, exhibits a lower elastic modulus than in thorough-the-thickness direction, whereas the Poisson coefficients obtained along the two main directions were approximately the same. Finally, the stiffer PVC foam of this experimental campaign was analysed.

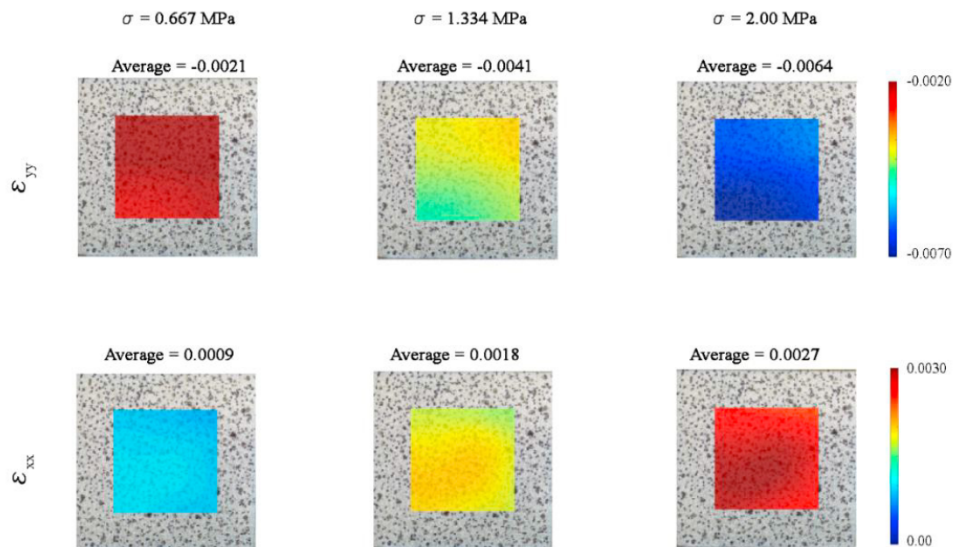


Fig. 7 Divinycell H200 thorough-the-thickness: Strain Maps obtained by DIC for different load levels (0.667, 1.334 and 2.00 MPa).





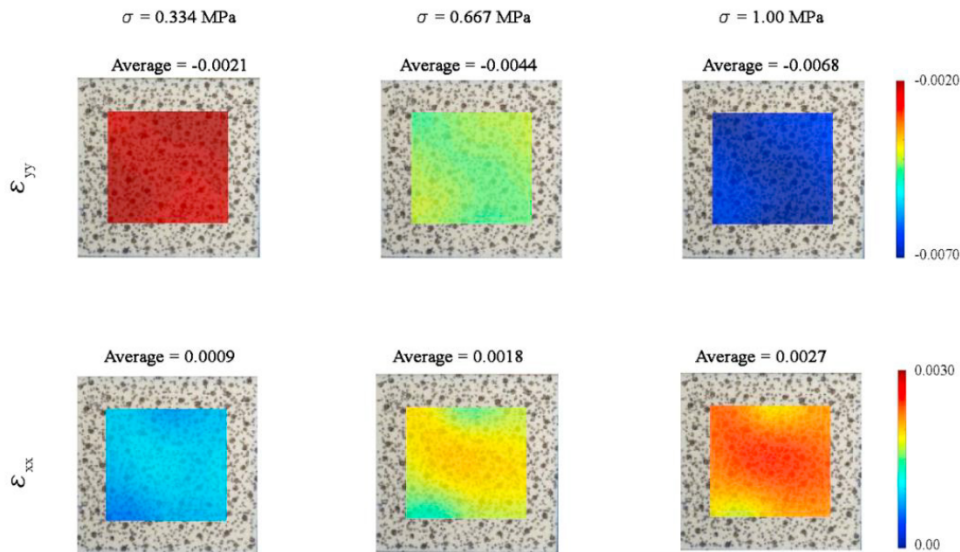


Fig. 8 Divinycell H200 in-plane: Strain Maps obtained by DIC for different load levels (0.334, 0.667 and 1.00 MPa).

As reported in Fig. 7, the strain maps of the PVC foam H200, along the through-the-thickness direction, were stored for a three load level respectively equal to 0.667, 1.334, 2.0 MPa. In this case, the elastic modulus estimated by using DIC procedure is in excellent agreement with that declared by the producer. Indeed, the percentage error is smaller than the other smaller analysed foams. To concern the evaluation of the Poisson coefficient, it appears to be equal to 0.43. Finally, the PVC foam H200 was also tested along the in-plane direction with the aim to estimate the grade of anisotropy of this material.

The obtained elastic parameters of the investigated foams are summarised in Tab 1 and 2.

### 3. Conclusions

The present paper proposes an experimental procedure aimed to detect the elastic properties of three different densities of polymeric foam material. The compression tests are conducted in accordance with ASTM Standard (2010), which prescribes a methodology to measure the elastic properties of Rigid Cellular Plastics. However, the experimental tests reveal that PVC foams are affected by the tendency to produce localised deformation due to the local collapse of cells under compression. This phenomenon produces an erroneous estimation of the elastic properties, which is overcome by using the DIC. The results show that PVC foams seem to be highly anisotropic with a ratio between the in-plane and through-thickness stiffnesses equal to 0.4-0.6. Excellent agreement in terms of elastic moduli of elasticity obtained by using the DIC and those declared by the product datasheet are obtained.

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